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RESEARCH MEMORANDUM

CORRELATION OF LABORATORY SMOKE TEST WITH CARBON DEPOSITION IN TURBOJET COMBUSTORS

By Arthur M. Busch

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

CORRELATION OF LABORATORY SMOKE TEST WITH CARBON DEPOSITION IN TURBOJET COMBUSTORS

By Arthur M. Busch

SUMMARY

A correlation of carbon deposition of 19 fuels in a turbojet combustor as a function of the boiling point and of the flame height at the sooting point of the fuels in a simple wick lamp has been developed for a particular combustor operating at a single set of conditions. Two similar investigations with different combustors, operating conditions, and nine different fuels yielded similar correlations on the same graph. The simple wick lamp is suggested to be of possible value in the evaluation of turbojet fuels.

INTRODUCTION

Because excessive carbon deposition in turbojet combustors may be detrimental to optimum engine operation, it is desirable to be able to evaluate the carbon-forming tendencies of fuels. Such evaluations have been made on full-scale turbojet engines, on single combustors from full-scale turbojet engines, and on small-scale combustors. Because investigations in combustors are time-consuming and require special equipment to provide air services it would be desirable to establish a simple laboratory test that would accurately predict the carbon-forming tendencies of a fuel. If such a test were developed it might be useful in the specification tests by which fuels are purchased.

In order to establish the validity of any proposed laboratory test, it is necessary to have experimental data on the carbon deposits from a variety of fuels. To a limited extent such data have been obtained for nineteen fuels in a $10\frac{3}{8}$-inch annular combustor (reference 1), on three AN-F-58 and one AN-F-32 type fuels in a J33 single combustor (reference 2), and on eight fuels in a J31 engine (reference 3). In references 1 and 2, correlations of the carbon deposition with the boiling point and the hydrogen-carbon

ratio of the fuels were established by which a satisfactorily accurate estimate could be made of the carbon-forming tendencies of a fuel under a variety of conditions.

The determination of the hydrogen-carbon ratio requires specialized equipment and skilled personnel. It is therefore desirable to establish the carbon-forming tendencies of a fuel on the basis of a more simple, reproducible test that could easily be made by laboratory technicians. Of several such tests examined, the height of flames at the sooting point, as reported in references 4 and 5, appeared most promising. The maximum height of smoke-free flames was shown to be dependent upon hydrocarbon type and molecular size and structure. Carbon deposition in turbojet combustors, likewise, has been related to these fuel variables in references 1 to 3 and in the investigations cited in reference 1. Simple wick-lamp tests have been widely used in the petroleum industry to specify the burning quality of kerosene (reference 6).

In an investigation conducted at the NACA Lewis laboratory and presented herein, the maximum height of smoke-free flames was found to be related to the carbon-forming tendencies of fuels. A function of this flame height, when combined with the volumetric average boiling point, yielded a satisfactory correlation with the carbon depositions of the 19 fuels listed in reference 1. The evaluation of a simple lamp test correlating the maximum height of a smoke-free flame with the carbon deposits found in the combustor experiments of references 1 to 3 is presented.

APPARATUS

Two lamps that have been previously used to evaluate the smoking tendencies of fuels are the Davis factor lamp (reference 6) and the smoke point of kerosene test lamp standardized by the Institute of Petroleum Technologists (hereinafter designated I.P.T. lamp) (reference 7). The Davis factor lamp uses an ice-cooled porcelain surface over a chimney to collect and indicate carbon. The I.P.T. lamp burns in a relatively large enclosure with the smoke point determined by observation of the flame. The lamp used in the work reported herein (fig. 1) had the fount, wick guide, and wick of the I.P.T. lamp and the chimney and smoke collector of the Davis lamp. The additions to the I.P.T. lamp produced a roughly 25-percent higher and more easily measured flame. A mirrored millimeter scale was placed behind the chimney so that the flame dimensions could be observed by telescope from the outside of a transparent draft-preventing hood.

1210

PROCEDURE AND RESULTS

The maximum height h of smoke-free flame was measured in millimeters for each of the fuels reported. Fuel is poured into a clean fount and the wick tube, fitted with a dry wick trimmed square to protrude about 1/8 inch, is screwed into the fount. The fount assembly is then placed in its holder after the top of the wick guide has been adjusted so that the wick guide, its mirrored image, and the zero of the scale coincide when viewed through the telescope. The chimney is raised to permit lighting of the wick and the flame height is adjusted to slightly under the sooting point by the elevation of the fount and the wick in the wick guide. After the lamp has been allowed to burn a few minutes to reach equilibrium, the maximum height is determined at which the flame burns without depositing soot on the ice-cooled porcelain surface placed above it. With the exception of fuels producing very low flames at the sooting point (aromatics), the flame heights could be reproduced to within 3 to 5 percent of their heights by this method.

Values of tendency to smoke 320/h were used in this report as in reference 4 so that large values of smoking tendency would correspond to large values of undesirable properties (for example, aromatics, carbon). The constant 320 was chosen in reference 4 to bring the smoking tendencies into the same numerical range as the flame height of the average clean-burning kerosene.

Carbon depositions of 19 fuels burned in a $10\frac{3}{8}$-inch annular combustor are reported in reference 1. A correlation graph of these data as a function of volumetric average boiling point and hydrogen-carbon weight ratio at the single set of operating conditions of 2 hours at sea level and 50-percent rated engine speed is presented in figure 2 (fig. 8, reference 1).

The converging lines of constant hydrogen-carbon ratio of reference 1 were replaced herein by parallel lines of tendency to smoke by taking the same correlation line in the right quadrant and plotting volumetric average boiling point in the left quadrant as a function of the logarithm of the carbon deposited (transferred to the ordinate through the chosen correlation line). (See fig. 3.) The points for each of the 19 fuels (not presented in this report) were labeled with their values of tendency to smoke and it was found that they could be satisfactorily approximated by logarithmically spaced parallel lines of equal tendency to smoke, as shown in figure 3. The same scales of carbon deposition and volumetric average boiling point as in figure 2 are used. The data for each fuel represent a

plot of the amount of carbon as determined in the $10\frac{3}{8}$-inch combustor and a function of tendency to smoke and boiling temperature. The equation representing the correlation line is

$$\log W_c = 1.47 \log \frac{320}{h} + 0.00131\ t - 1.233$$

where

W_c weight of carbon deposit predicted, grams

$\frac{320}{h}$ tendency to smoke

t volumetric average boiling temperature, $^{\circ}F$

The horizontal displacement of each point from the correlation line is a measure of the inaccuracies of the smoke-lamp method in predicting the carbon deposition in the combustor. The carbon deposition predicted by both flame height and hydrogen-carbon measurements are shown in table I along with the amount actually obtained in combustor tests. The two correlations appear quite comparable in reliability.

The same type of correlation was also sought for three experimental AN-F-58 and one AN-F-32 fuels for which carbon deposits were determined in a J33 single combustor run under the five different operating conditions reported in reference 2. Five lines correlating the test and combustor data were obtained by plotting the carbon-deposition data as the same function of volumetric average boiling temperature and tendency to smoke as in the ordinate of figure 3. The flame height, volumetric average boiling point, and carbon-deposition values for these fuels are shown in table II, and the resulting correlation graph in figure 4. Again the horizontal displacement of the points from their respective lines is an indication of the deviations of the smoke-lamp-predicted carbon deposition from that actually obtained in the burner.

At another laboratory, carbon depositions of eight fuels were investigated in a J31 engine operating at sea-level static conditions for 30 hours (reference 3). Five of these fuels, listed and partly described in table III, were available to this laboratory for flame-height measurements. Plotting values of the same properties as in the previous correlations yields the graph in figure 5. The AN-F-28 aviation gasoline fuel contained 4.6 ml TEL per gallon, which added to the weight deposited in the combustor and displaced this data point to the right. The remaining data approximated a straight line.

1210

DISCUSSION

Any proposed test to evaluate the carbon-forming tendencies of turbojet fuels will ultimately be required to designate the suitability of any particular fuel for use in field operations. The ability of the correlation described herein and in reference 1 to accept or reject fuels accurately may be judged if the limits of allowable carbon deposits in this combustor are specified. The amount of deposit, as reflected in these single-combustor experiments, that constitutes a disadvantageous field operating condition is unknown. If the amount of deposit by AN-F-32 fuel is assumed to be acceptable, and the deposit of a fuel composed of 50-percent AN-F-32 fuel and 50-percent aromatic solvent is assumed to be excessive, then the limit is set somewhere between 8.0 and 26.5 grams for the case of the $10\frac{3}{8}$-inch combustor when operated under the conditions of figure 2.

If the maximum permissible carbon deposit in the $10\frac{3}{8}$-inch combustor is arbitrarily set at 10 grams, then the correlation of tendency to smoke and the boiling point accurately predicts the acceptance or failure of 18 of the 19 fuels examined. At this same 10-gram level, the hydrogen-carbon boiling-point correlation gives the correction prediction for 17 of the 19 fuels.

Similarly, at a 20-gram level, the smoke-lamp correlation yields the correct prediction for 17 of the 19 fuels, whereas the hydrogen-carbon method predicts all 19 fuels correctly. At a 30-gram level, both methods predict correctly for 17 of the 19 cases.

The two correlation procedures are therefore comparable in their ability to pass or reject fuels. The smoke-lamp method has an advantage in being a simpler technique to apply in the laboratory.

Although the correlation shown in figure 3 is for only one condition in one combustor, it is probable that similar correlations can be developed for a variety of conditions in any combustor. The small range of carbon depositions in the tests other than that of reference 1 do not provide adequate data to develop a more general correlation at present. A wider use of this or a similar lamp test might, however, prove its value as a fuel-specification test.

SUMMARY OF RESULTS

Applying data of flame height at the sooting point of 28 fuels to carbon-deposition and boiling-temperature data that had been

1210

obtained from three investigations of carbon deposition resulted in the following correlations:

1. A plot of carbon deposition for 19 fuels in an annular combustor as a function of flame height at the sooting point and volumetric avarage boiling point gave good correlation of the data. This correlation is applicable to a particular turbojet combustor operating at a single set of conditions.

2. The accuracy of this correlation was of the same order as that obtained in a similar hydrogen-carbon correlation where the same carbon deposition data were plotted as a function of volumetric average boiling point and hydrogen-carbon ratio.

3. The correlation based on the flame-height apparatus mentioned in the first result was also found to be satisfactory when applied to data obtained on a J33 combustor with three different wide-boiling-range AN-F-58 turbojet fuels and one AN-F-32 turbojet fuel. The method was also found to apply satisfactorily to carbon-deposition data on five fuels obtained at another laboratory.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio.

1210

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TABLE I - PHYSICAL PROPERTIES, CARBON DEPOSITIONS, AND PREDICTED CARBON DEPOSITIONS OF 19 FUELS

[Data from reference 1]

NACA

Data point	NACA fuel	Fuel	Volumetric average boiling temperature, t (°F)	Flame height at the smoking point, h (mm)	Tendency to smoke, $\frac{320}{h}$	Carbon deposition, grams		
						Actual	Predicted	
							Hydrogen-carbon weight ratio method	Lamp method
		Paraffinic hydrocarbon fuels						
1	46-111	Commercial isoheptane	182	77	4.2	1.0	1.0	0.85
2	46-254	Paraffinic solvent	348	53.5	6.0	1.8	1.8	2.2
		Olefinic hydrocarbon fuels						
3	46-152	Diisobutylene	211	28.5	11.2	4.1	2.0	3.8
4	47-50	n-Hexadecene-1	523	85	3.9	2.3	16.0	2.1
		Aromatic hydrocarbon fuels						
5	46-219	Benzene	172	6.0	53	33.5	29.5	34.0
6	47-152	50-percent benzene and 50-percent aromatic solvent	264	6.6	48.5	56.1	52	39.0
7	46-338	Ethylbenzene	270	5.3	51	44.8	47	42.7
8	46-71	Xylenes	278	6.0	53	52.5	47	46.3
9	46-133	Aromatic solvent	335	6.4	50	51.5	57	49.0
10	47-363	30-percent α- and β-monomethylnaphthalene and 70-percent aromatic solvent	369	5.7	56	140.5	114	66.1
11	47-173	Triisopropylbenzene	444	5.1	63	88.3	79	98.6
12	46-216	α- and β-monomethylnaphthalene	459	4.6	70	133.9	480	120
		Mixed hydrocarbon fuels						
13	47-150	50-percent commercial isoheptanes and 50-percent benzene	171	7.3	44	15.7	10.7	25.5
14	44-821	AN-F-28R	215	23	13.9	1.4	1.8	5.4
15	47-153	50-percent commercial isoheptanes and 50-percent AN-F-32	291	38	8.4	3.3	3.3	3.2
16	47-151	50-percent AN-F-32 and 50-percent aromatic solvent	360	9.5	33.7	26.5	29.5	30.5
17	47-188	AN-F-32	376	26	12.3	8.0	9.6	7.3
18	47-114	Michigan crude	517	27.5	11.6	6.4	17.1	10.2
19	47-115	Diesel oil	524	20.2	15.8	31.7	28.2	16.4

TABLE II - PHYSICAL PROPERTIES AND CARBON DEPOSITION OF FOUR EXPERIMENTAL TURBOJET FUELS BURNED IN J33 SINGLE COMBUSTOR AT 90-PERCENT NORMAL RATED ENGINE SPEED

[Data from reference 2]

NACA fuel	Fuel	Volumetric average boiling temperature, t (°F)	Flame height at the sooting point, h (mm)	Tendency to smoke, $\frac{320}{h}$	Carbon deposition, grams				
					Simulated altitude, ft				
					20,000				35,000
					Running time, hr				
					2	4	6	10	6
48-306	AN-F-32, JP-1	378	18.6	17.2	6.5	12.2	16.5	24.4	11.1
48-249	AN-F-58 (mixed batch)	312	26.2	12.2	3.1	6.1	8.9	14.9	5.9
48-258	Fuel 48-249 with 8-percent furnace oil added	329	24.8	12.9	3.3	7.4	11.3	19.7	7.0
48-279	Fuel 48-249 with 8-percent furnace oil and 13-percent Indocene added	349	13.0	24.6	[a]6.9	13.2	[a]19.4	26.7	11.9

[a]Average of three runs.

TABLE III - PHYSICAL PROPERTIES AND CARBON DEPOSITION OF FIVE FUELS BURNED IN J31 ENGINE

[Data from reference 3 at sea-level static pressure; fuel-flow, 500 gal/hr; running time, 30 hr]

Fuel	Volumetric average boiling temperature,[a] t (°F)	Flame height at the sooting point, h (mm)	Tendency to smoke, $\frac{320}{h}$	Average combustor-liner and dome carbon (grams)
PPF 45-7	336	34.5	9.3	6.8
AN-F-32	374	[b]18.6	17.2	20.4
PPF 45-6	410	10.7	29.9	29.5
AN-F-28	207	[b]33.0	9.7	[c]30.3
PPF 47-3	290	11.5	27.8	34.0

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[a]Average of 10-, 50-, and 90-percent evaporated temperatures.

[b]Different batch of same specification fuel used in flame-height measurement.

[c]Fuel contained 4.6 ml TEL/gal.

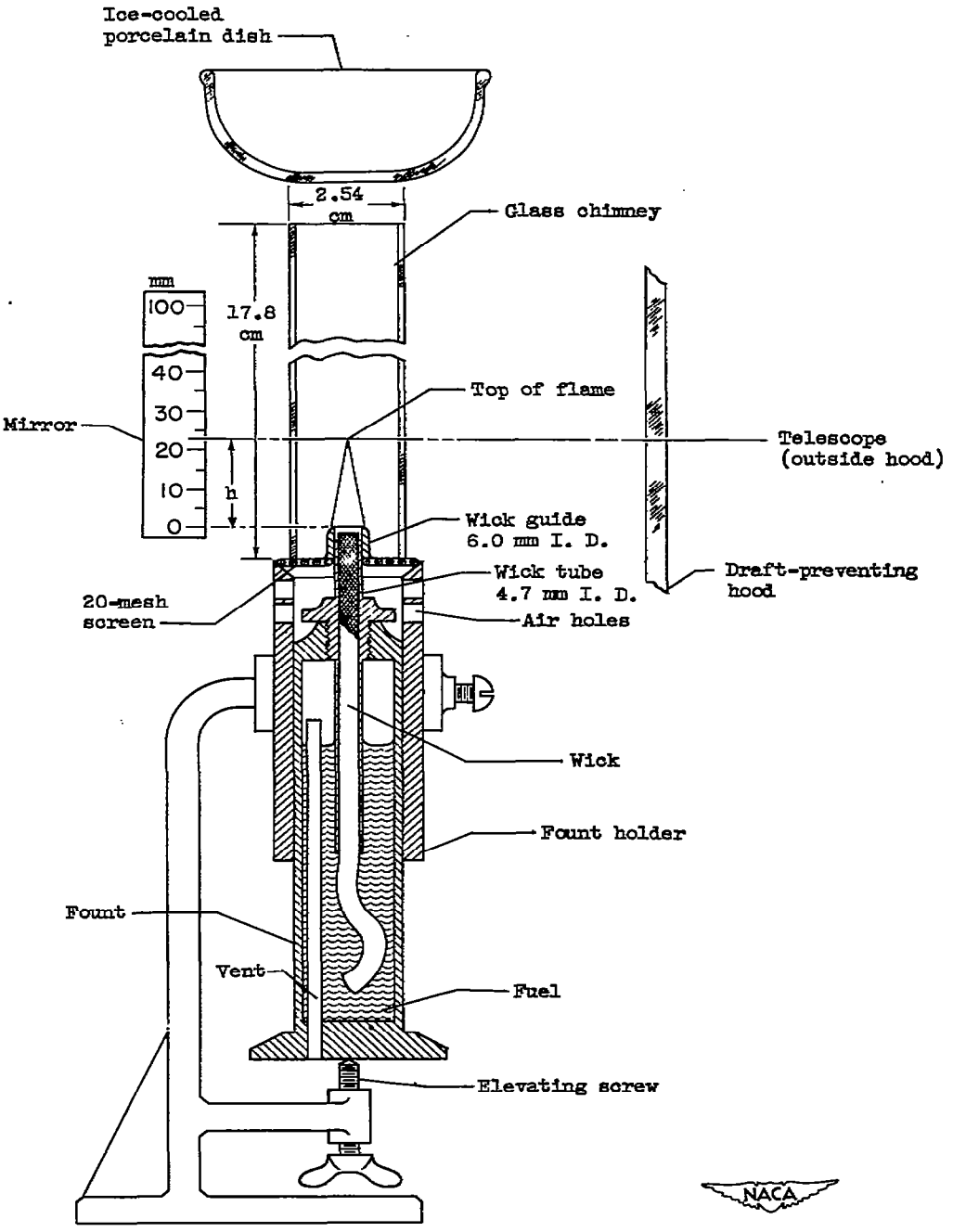

Figure 1. - NACA modified Davis factor lamp.

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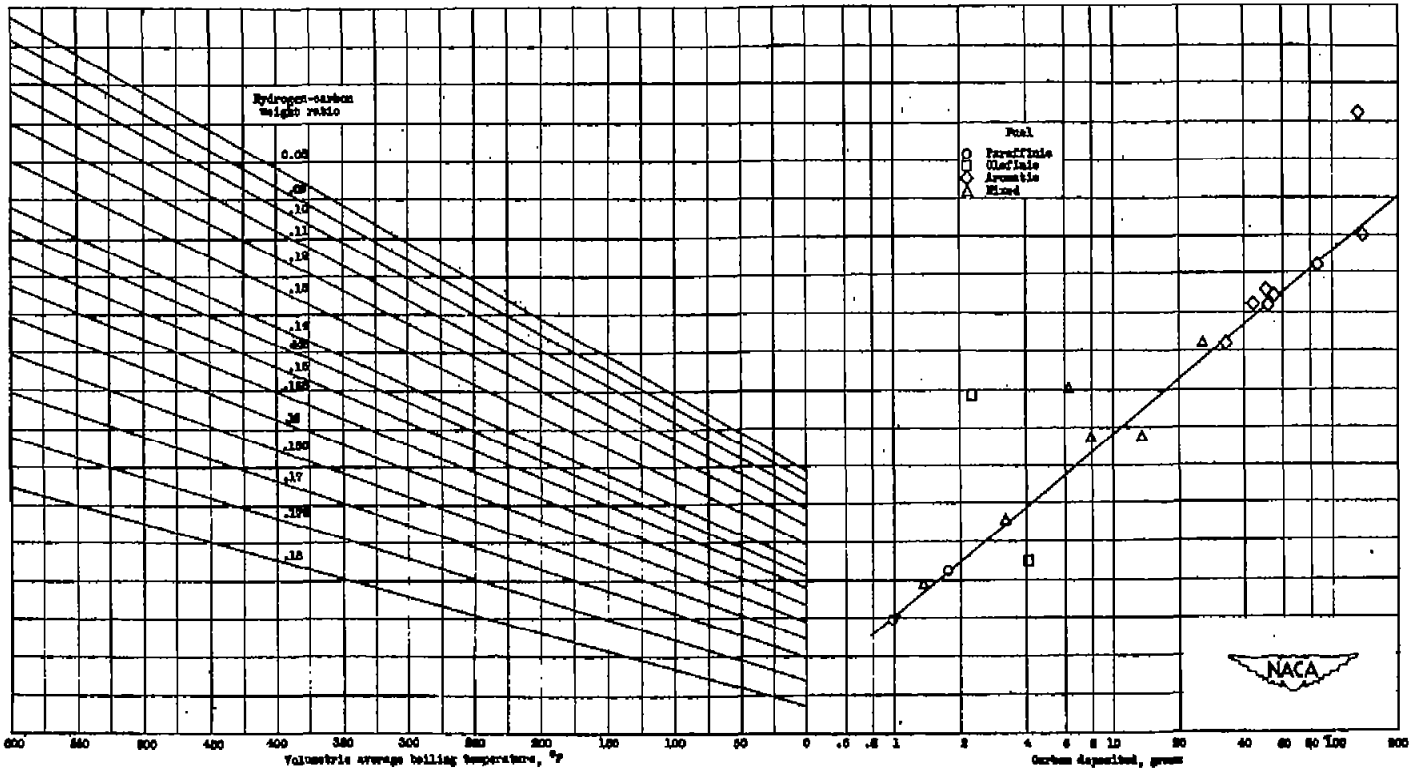

Figure 9. - Carbon deposition of 19 fuels as determined by volumetric average boiling point and hydrogen-carbon weight ratio. Annular combustor diameter, $1\frac{5}{8}$ inches; inlet-air total pressure, 40 inches mercury absolute; inlet-air total temperature, 100° F; fuel flow, 187.5 pounds per hour; over-all fuel-air ratio, 0.0178; running time, 2 hours. (Fig. 8, reference 1.)

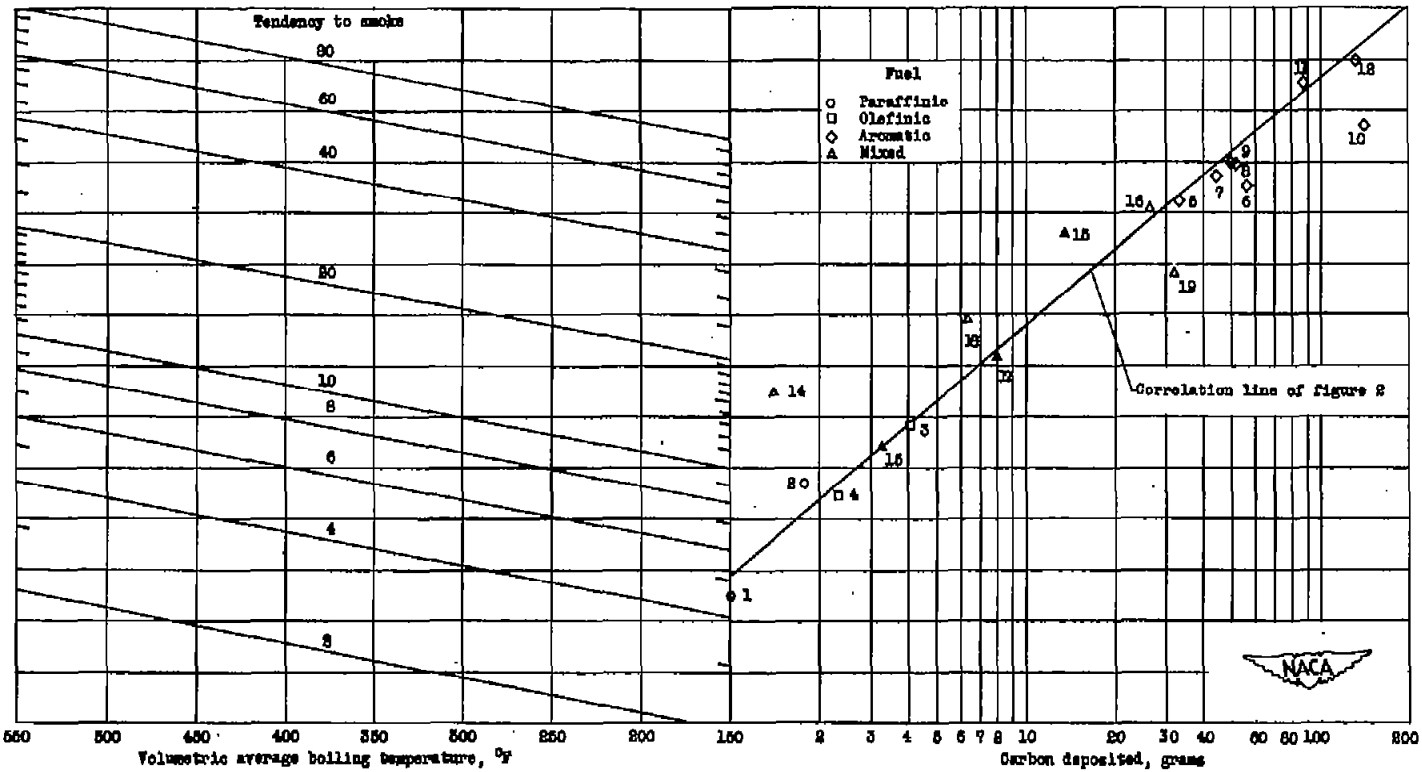

Figure 3. - Carbon depositions of 19 fuels as determined by volumetric average boiling point and sooting point. Data point numbers refer to table I.